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Proterozoic crustal evolution in southcentral Fennoscandia

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ABSTRACT

The Transscandinavian Igneous Belt (TIB) and the Eastern Segment of the Southwest Scandinavian Domain reflect advanced stages of continental growth within the Fennoscandian Shield. The relationship between the two units is not clear, mainly because N-S trending shear zones of the Protogine Zone transect the border zone. The main goal of this thesis has been to investigate rocks in the border zone and to conclude how these rocks differ from each other. In this work two volcanic sequences and 24 granitoids in the border area, near Jönköping, were examined. The thesis reports geochemical and Sm-Nd isotope data as well as U-Pb ion microprobe zircon dates for extrusive and intrusive rocks in the southwestern part of the TIB and intrusive rocks in the eastern part of the southern Eastern Segment.

The TIB rocks are subdivided into TIB-0, TIB-1 and TIB-2 groups based on their ages. In this work, the Habo Volcanic Suite and the Malmbäck Formation are dated at 1795±13 Ma and 1796±7 Ma respectively, which establishes that they are part of the TIB-1 volcanic rocks. The Malmbäck Formation is situated in the southwestern part of TIB, east of the Protogine Zone, whereas the Habo Volcanic Suite is located c. 50 km northwest of the Malmbäck Formation, between shear zones of the Protogine Zone. Both suites comprise mafic to felsic components and the Malmbäck Formation includes one of the largest mafic volcanic rock units of the TIB-1. The Malmbäck Formation comprises fairly well preserved volcanic rocks, with primary textures, although mineral parageneses in some rocks suggest metamorphism at up to epidote-amphibolite facies conditions. Amphibolites facies metamorphism and deformation has largely obscured primary textures of the Habo Volcanic Suite. Dating of a Barnarp granite which intrudes the Habo Volcanic Suite gave an age of 1660±9 Ma, corresponding to TIB-2. The occurrences of Malmbäck Formation megaxenoliths within TIB-1 granitoids are explained by stoping. Geochemical signatures of the two metavolcanic rock suites suggest emplacement in an active continental margin setting. It is further suggested that the TIB regime was complex, similar to what is seen in the Andes today, with different regions characterised by subduction-related magmatism, Andinotype extension as well as local compression.

Twenty-one granitoids (including the granite intruding the Habo Volcanic Suite), across and in the border zone between the TIB and the Eastern Segment, were dated by U-Pb zircon ion probe analysis. Eighteen of the granitoids yielded TIB-2 magmatic ages, ranging between 1710 and 1660 Ma. Eighteen granitoids were analyzed for geochemistry and Sm-Nd isotopes. The geochemical and isotopic signatures of the granitoids proved to be similar, supporting the theory that the TIB and the Eastern Segment originated from the same type of source and experienced the same type of emplacement mechanisms. Further, it is concluded that the TIB-2 granitoids, from both the TIB and the Eastern Segment, were derived by reworking of juvenile, pre-existing crust, in an essentially east- to northeast-directed subduction environment. The U-Pb zircon ion microprobe analyses also dated zircon rims which formed by metamorphism during the 1460-1400 Ma Hallandian-Danopolonian orogeny, in granitoids of both the southern Eastern Segment and the western TIB. Leucosome formation, for two samples was dated at 1443±9 Ma and 1437±6 Ma. An aplitic dyke, cross-cutting NW-SE to E-W folding and leucosome formation in the Eastern Segment was dated at 1383±4 Ma, which sets a minimum age for the NW-SE to E-W folding in the area. Hence, it is concluded that the leucosome formation and the NW-SE to E-W folding in the investigated part of the Eastern Segment as well as NW-SE to E-W penetrative foliation and lineation in the western TIB took place during the 1470-1400 Ma Hallandian-Danopolonian orogeny.

No c. 970 Ma Sveconorwegian ages were recorded in any of the areas investigated. Nevertheless, Sveconorwegian (in addition to earlier) block movements caused uplift of the Eastern Segment relative to the TIB, revealing from west to east: (1) the highly exhumed metamorphosed southern Eastern Segment, in which the effects of both the Hallandian-Danopolonian and the Sveconorwegian orogenies can be seen, (2) the partly exhumed westernmost TIB-2 showing the effects of the Hallandian-Danopolonian orogeny only, and (3) the easternmost TIB-2 granitoids, as well as the supracrustal and shallow emplaced TIB-1 granitoid rocks in the east. The main part of TIB was apparently unaffected by the Hallandian-Danopolonian orogeny, apart from the intrusion of subordinate felsic bodies and mafic dykes. Tilting and other block movements within the Eastern Segment also occurred during the uplift, revealing lower crustal sections in the south compared to the northern part.

Keywords: Transscandinavian Igneous Belt, TIB, Eastern Segment, Habo Volcanic Suite, Malmbäck Formation, U-Pb zircon ion probe dating, Nd isotopes, geochemistry, Hallandian, Danopolonian

This doctoral thesis includes the following papers, which are referred to in the text by their Roman numerals:

I   Appelquist, K., Cornell, D. & Brander, L., 2008. **Age, tectonic setting and petrogenesis of the Habo Volcanic Suite: Evidence for an active continental margin setting for the Transscandinavian Igneous Belt**. GFF 130, 123-138. Reprinted with permission from GFF.

The project was initiated by S.Å. Larson, who also contributed to planning. Appelquist did the main part of the planning, field work, sampling, sample preparation, petrography, analysis (SEM, ICP-MS), ion probe work, interpretations, writing, figures and tables. Cornell contributed with LA-ICP-MS analysis and discussion. Brander contributed with field work and discussion.

II   Appelquist, K., Eliasson, T., Bergström, U. & Rimša, A. **The Palaeoproterozoic Malmbäck Formation in S Sweden: age, composition and tectonic setting**. GFF 131, 229-243. Reprinted with permission from GFF.

Appelquist did the planning, field work, sampling, sample preparation, petrography, analysis (SEM), interpretations and writing in collaboration with Eliasson and Bergström. Figures and tables were done by Appelquist. Rimša did the ion probe dating.

III   Appelquist, K. & Johansson, Å. **Nd isotope systematics of 1.8 Ga volcanic rocks within the Transscandinavian Igneous Belt, southcentral Sweden**. Submitted to GFF.

Appelquist did the planning, sampling, figures, tables and writing. The sample preparation, isotope work, discussion and interpretations were done by Appelquist in collaboration with Johansson.

IV   Brander, L., Appelquist, K., Cornell, D. & Andersson, U.B. **1.71-1.60 Ga crust formation and 1.46-1.41 Ga Hallandian-Danopolonian deformation – a 300 Ma common history of the Transscandinavian Igneous Belt and the Eastern Segment**. Manuscript.

The project was initiated by S.Å. Larson and J. Stigh. Brander and Appelquist did the planning, field work, sampling, sample preparation, ion probe work, discussion and interpretations. Brander did the main part of the writing as well as most figures and tables. Cornell contributed with data, discussion and interpretations. Andersson also contributed with discussion and interpretations.

V   Appelquist, K., Brander, L., Johansson, Å., Andersson, U.B. & Cornell, D. **Geochemical and Sm-Nd isotope signatures of granitoids from the Transscandinavian Igneous Belt and the Eastern Segment of Sweden**. Submitted to Geological Journal.

Appelquist and Brander did the planning, field work, sampling, sample preparation, isotope work, discussion and interpretations. Appelquist did the main part of the writing as well as most figures and tables. Johansson contributed with isotope work, discussion and interpretations. Andersson and Cornell also contributed with discussion and interpretations.

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Hej svejs, grus och gnejs!

Introduction

The Fennoscandian (or Baltic) Shield of the East European Craton is mainly composed of crustal units accreted to the shield's oldest part, the >2.6 Ga old Archean craton (cf. Gaál & Gorbatschev 1987) in the northeast. The Svecofennian Province, consisting of both plutonic and supracrustal rocks, was the first province to be accreted to the Archean craton, and is considered to represent a collage of microcontinents and island arcs ranging in age between c. 2.1-1.8 Ga (e.g. Korja et al. 2006). Between c. 1.86 and 1.76 Ga, the Svecofennian Province experienced extensive reworking, generating granitoids both within the Svecofennian Province and along its western and southwestern borders (cf. Andersson 1991). Granitoids generated by east- to north-directed subduction, along the border of the Svecofennian Province, form the Transscandinavian Igneous Belt (TIB, Patchett et al. 1987). To the southwest the TIB grades into the metamorphosed Southwest Scandinavian Domain, which represents the final stage of continental growth within the Fennoscandian Shield (Gaál & Gorbatschev 1987).

This project was initiated by Sven Åke Larson and Jimmy Stigh, who suggested a study on the tectonic relationship between the TIB and the Eastern Segment of the Southwest Scandinavian Domain (Fig. 1). The thesis deals with extrusive and intrusive rocks in the southwestern part of the TIB as well as intrusive rocks in the eastern part of the southern Eastern Segment. The primary effort has been to compare the two domains with regard to their isotopic systems and geochemistry and to investigate the tectonic setting in which the rocks were formed.

It is concluded that the TIB magmatic rocks were produced in a convergent continental margin setting of Andean type, as previously suggested by e.g. Wilson 1982; Nyström 1982, 1999; Andersson 1991; Åhäll & Larson 2000, as the result of long-lived east- and north-directed subduction (e.g. Andersson 1991; Andersson et al. 2004a and references therein).

Most researchers agree that the construction of post-Archean continental crust was related to subduction, but how continents grew in arc systems is not yet fully understood. Continental crust is believed to be derived by partial melting of the mantle and various mechanisms have been suggested for the growth of continents. The most important mechanism is probably magma accumulation by crustal underplating and by terrane collisions with continental margins (Rudnick 1995). By these mechanisms large volumes of juvenile magma from the mantle are added to both oceanic and continental margin arcs.

The TIB and the Eastern Segment represent advanced stages of continental growth within the Fennoscandian Shield. The relationship between the two provinces is not obvious, partly due to the fact that N-S trending shear zones of the Protogine Zone transect the border zone, but it has been suggested that the Eastern Segment is the metamorphosed counterpart of the TIB (e.g. Lindh & Gorbatschev 1984; Lindh & Persson 1990; Wahlgren et al. 1994; Connelly et al. 1996; Berglund et al. 1997; Söderlund et al. 1999, 2002, 2004a; Åhäll & Larson 2000; Andersson 2001). This theory is supported by the results of this study, which demonstrates similar Nd-isotope systematics, magmatic ages and shows that the c. 1.43 Ga Hallandian-Danopolonian orogeny affected at least parts of both domains. A westerly increase in metamorphism across the border zone may be related to the progressive increase in exhumation, exposing deeper parts of the crustal section from the TIB in the east to the Eastern Segment in the west. It is further suggested that the TIB-1 rocks in the

southern TIB were emplaced at shallow, near-surface levels at c. 1.8 Ga. Younger TIB-2 plutonic rocks within the western part of TIB represent somewhat deeper crustal levels, whereas the gneisses of the southern parts of the Protogine Zone and the Eastern Segment represent TIB-2 rocks from even greater crustal depth, that were metamorphosed during the Hallandian-Danopolonian and the Sveconorwegian orogenies, before being uplifted and eroded to the present-day surface.

Review of the concepts of the Transscandinavian Igneous Belt (TIB) and the Eastern Segment

One of the major geological units of the Fennoscandian Shield is the 1.86-1.65 Ga Transscandinavian Igneous Belt (TIB, Patchett et al. 1987; Åhäll & Larson 2000; Högdahl et al. 2004; Wik et al 2005a and references in these publications). The TIB is dominated by relatively undeformed, dominantly coarse K-feldspar porphyritic granitoids, and subordinate gabbroids and volcanic rocks, stretching c. 1500 km N-S across the entire shield (southernmost part shown in Fig. 1). The TIB may be subdivided geographically into the Småland-Värmland Belt, the Dala Province, the Rätan Batholith, the Sorsele granitoids and the TIB-windows in the Caledonides (cf. Högdahl et al. 2004 and references therein). Some authors also include the mostly undeformed Revsund granitoid suite (e.g. Gorbatschev & Bogdanova 1993; Andersson 1997a) and the c. 1.75 Ga basement of the Blekinge Province (e.g. Kornfält 1996; Johansson et al. 2006).

Ages for the TIB range between 1.86 and 1.65 Ga (Högdahl et al. 2004; Table 1 and references therein) and show an overall southward to southwestward younging trend (Åhäll & Larson 2000). Based on

magmatic ages, the TIB has traditionally been subdivided into different age groups. The groupings used in this thesis are: TIB-0 at 1.86-1.84 Ga (cf. Ahl et al. 2001 and references in Table 1), TIB-1 at 1.81-1.76 Ga (Larson & Berglund 1992) and TIB-2 at 1.71-1.65 Ga (Andersson & Wikström 2004). Larson & Berglund (1992) divided the last episode of TIB-magmatism into two separate events: the TIB-2 at 1.71-1.69 and the TIB-3 at 1.67-1.65 Ga, but were not convinced there was a hiatus between the two. Indeed, the precision of the present data is not sufficient to justify the separation into the two latter age groups (cf. Paper IV).

The granitoids of all three age groups generally show monzogranitoid, alkali-calcic, alkali-rich characteristics (Ahl et al. 1999) of A- and I-type compositions (Gorbatschev
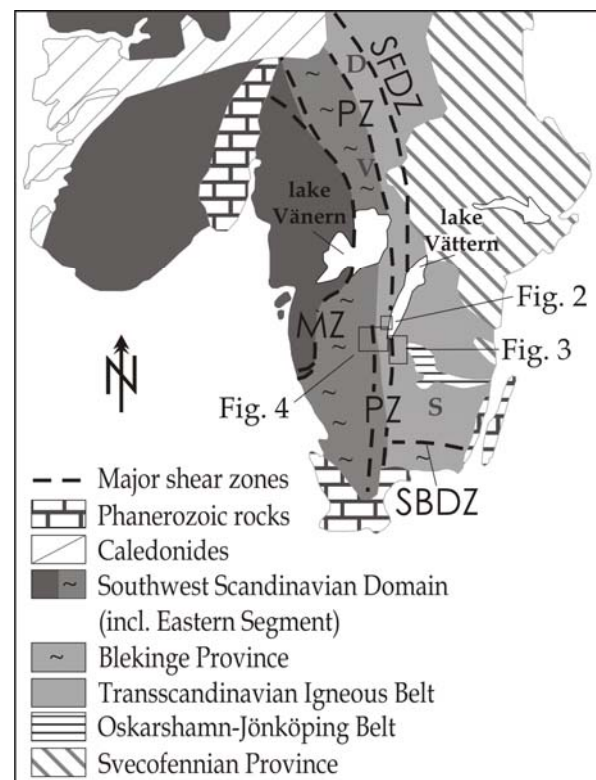

Fig. 1. Simplified geological map of southwestern Fennoscandia (after Gaál & Gorbatschev 1987; Koistinen et al. 2001). MZ: Mylonite Zone, PZ: Protogine Zone, SBDZ: Småland-Blekinge Deformation Zone, SFDZ: Sveconorwegian Frontal Deformation Zone. D: Dalarna, S: Småland, V: Värmland.

2004). Deviations from the alkali-calcic trends occur e.g. in the calc-alkalic Revsund granite and in the Småland-Blekinge region in SE Sweden, where calc-alkalic trends have been reported north and south of the Oskarshamn-Jönköping Belt (e.g. Gorbatschev 2004; Thomas Eliasson pers. comm.).

The 1.83-1.82 Ga Oskarshamn-Jönköping Belt is situated within the Småland-Värmland Belt (Fig. 1), but ages and geochemical trends suggest that it is a distinct geological unit compared to TIB (Mansfeld 1996; Åhäll et al. 2002; Mansfeld et al. 2005). In the north the TIB disappears beneath the Caledonides, but is exposed in basement windows within and also on the western margin of the Scandinavian Caledonide nappes (Gorbatschev 1980). To the east the TIB is bordered by the Svecofennian Province. However, the relationship between the Småland-Värmland Belt in the southern part of the TIB and the Svecofennian Province is a controversial matter, mainly because of the difficulties to strictly define TIB and Svecofennian rocks. Geochemical signatures as well as ages in the two domains overlap. Structurally the rocks of the TIB-0 generation range from massive to strongly deformed amphibolite-facies augen gneisses, a transition which in many places is gradual. The Svecofennian rocks along the border of the Småland-Värmland Belt exhibit a granulite facies peak in an overall regional amphibolite facies metamorphism regime; and ages of contact and regional metamorphism also overlap in the range 1.86-1.78 Ga (Wikström & Andersson 2004). Thus, the ages as well as metamorphic imprints of the TIB-0 rocks completely overlap those of the late orogenic rocks within the Svecofennian Domain, suggesting that coeval tectonic processes were responsible for both magmatic suites (cf. Andersson 1991; Gorbatschev & Bogdanova 1993).

To the south the TIB is covered by Phanerozoic cover rocks and to the southwest the TIB passes into the c. 1.78-0.94 Ga polymetamorphic Southwest Scandinavian Domain (cf. Gaál & Gorbatschev 1987; and compilation in Bingen et al. 2008a). Other terms used for the southwestern part of the Fennoscandian Shield are the Sveconorwegian Orogen, the Sveconorwegian Province (Patchett & Bylund 1977; Berthelsen 1980), the Sveconorwegian Belt (e.g Park 1992), or the Gothian Orogen (e.g. Christoffel et al. 1999), but the definitions of these terms are somewhat ambiguous.

Gaál & Gorbatschev (1987) ascribed the term Southwest Scandinavian Domain to the westernmost part of the Fennoscandian Shield, consisting of strongly foliated rocks which have experienced 1.5-1.4 and 1.25-0.9 Ga metamorphism and is bordered to its east by the Protogine Zone. Gaál & Gorbatschev (1987) depicted the Protogine Zone as a sharp boundary between the rocks of the polymetamorphic Southwest Scandinavian Domain and the more well-preserved rocks to its east, but in contradiction to this they also described the granites of the TIB to *pass into* the orthogneisses. The term Sveconorwegian Province or the Sveconorwegian Orogen is usually referred to Berthelsen (1980) and Gorbatschev & Bogdanova (1993) and the terms are normally used for the southwestern part of the Fennoscandian Shield that has experienced *penetrative ductile deformation as well as spaced Sveconorwegian ductile deformation* (e.g. Andersson 2001). Hence, the eastern border of the Sveconorwegian Orogen or Province is defined by the Sveconorwegian Frontal Deformation Zone (SFDZ, Fig. 1; Wahlgren et al. 1994) north of lake Vättern and the eastern part of the Protogine Zone (PZ, Fig. 1) south of lake Vättern. Magmatic crystallization ages of rocks within the

Sveconorwegian Orogen range up to c. 1.80 Ga (Jarl & Johansson 1988; Person & Ripa 1993; Stephens et al. 1993; Lundqvist & Persson 1996; Paper I).

The term **orogen** is usually used for an orogenic belt or mountain belt that is produced where an oceanic plate converges against an overriding continental plate, which deforms by folding and thrusting and experiences arc magmatism and regional metamorphism (Best 2003). A **crustal province** is an orogen, active or exhumed, which records a similar range of isotopic ages and exhibits a similar postamalgamation deformational history (Condie 2005). Most crustal provinces and orogens are composed of **terranes** (e.g. Patchett & Gehrels 1998), which are fault-bounded crustal blocks that have distinct lithologic and stratigraphic successions and geologic histories different from neighboring terranes (Schermer et al. 1984).

In this thesis the term Southwest Scandinavian Domain is advocated for the westernmost part of the Fennoscandian Shield (Paper I-III, V). However, in Paper IV the term and definition of the Sveconorwegian Orogen is used. The Southwest Scandinavian Domain occupies most of southern Norway and southwestern Sweden (Fig. 1) and comprises several north-south trending units, separated from each other by ductile shear zones. These units have also been referred to as segments, sectors and blocks (Andersen 2005), or even terranes (e.g. Åhäll & Gower 1997), although the latter is controversial (Andersen 2005).

The Eastern Segment, which is the easternmost unit of the Southwest Scandinavian Domain, consists of penetratively deformed and metamorphosed rocks. It is dominated by granitoids ranging between 1.71 and 1.65 Ga in age (e.g. Johansson 1990; Johansson et al. 1993; Connelly et al. 1996; Christoffel et al. 1999; Larson et al. 1999; Söderlund et al.

1999, 2002; Alm et al. 2002; Scherstén et al. 2000; Andersson et al. 2002a; Austin Hegardt et al. 2005; Möller et al. 2007; Rimša et al. 2007; Bingen et al. 2008a). The Eastern Segment is roughly separated from the granitoid-dominated and only moderately reworked crust to the east by the western part of the Protogine Zone (PZ, Fig. 1), whereas the Mylonite Zone (MZ) defines the approximate western tectonic boundary (Berthelsen 1980; Stephens et al. 1996). Based mainly on differences in degree of deformation and c. 1.43 Ga Hallandian-Danopolinian or c. 0.97 Ga Sveconorwegian metamorphic ages, the Eastern Segment is divided into a northern and a southern part, with the border between the two approximately coinciding with lake Vänern. However, there is no distinct tectonic boundary between the two and Bingen et al. (2008a) also refer to a central part, located between lakes Vänern and Vättern, where no comprehensive investigations have been carried out.

North of lake Vänern only c. 0.97 Ga Sveconorwegian metamorphic ages have been found (e.g. Söderlund et al. 1999) and it has been concluded that the deformed granitoids of the northern Eastern Segment consist of reworked TIB-granitoids (Lindh & Gorbatschev 1984; Lindh & Persson 1990; Wahlgren et al. 1994; Söderlund et al. 1999). In the southern Eastern Segment most granitoids were migmatized and tectonically banded (Larson et al. 1986; Connelly et al. 1996; Larson et al. 1998) during both the 1.47-1.40 Ga Hallandian-Danopolonian (cf. Hubbard 1975; Christoffel et al. 1999; Söderlund et al. 2002; Austin Hegardt et al. 2005; Möller et al. 2007; Brander & Söderlund 2009) and the 1.10-0.92 Ga Sveconorwegian orogenies (Connelly et al. 1996; Andersson et al. 1999; Söderlund et al. 2002; Möller et al. 2007). Overlapping igneous ages and rock compositions suggest that the Eastern Segment granitoids south of

lake Vänern represent reworked granitoids of "TIB"-age (eg. Connelly et al. 1996; Berglund et al. 1997; Åhäll & Gower 1997; Åhäll & Larson 2000; Andersson 2001). Recent mapping by the Geological Survey of Sweden has also revealed porphyritic TIB-like rocks in the interior of the southern Eastern Segment (Lena Lundqvist pers. comm.). These rocks display the distinctive gneissosity, veining and banding typical of the Eastern Segment, although the characteristically porphyritic textures of the mesosomes indicate the presence of reworked TIB-rocks within the southern Eastern Segment.

The Protogine Zone has been variably used as the approximate border between TIB-0 and TIB-1 in the east and TIB-2 rocks in the west (e.g. Koistinen et al. 2001; Gorbatschev 2004) or as the border between the TIB in the east and the Eastern Segment in the west (e.g. Gorbatschev 1980), but it is important to remember that the Protogine Zone is not a sharp contact between two lithostratigraphic or tectonostratigraphic domains. It is a c. 25-30 km wide zone consisting of several individual shear zones of high strain and intense schistosity resulting in strongly foliated and folded granitoids and mylonites. Between the shear zones rather well-preserved zones of TIB rocks as well as younger rocks occur. Going westwards, the onset of penetrative deformation and migmatization within the rocks of the Eastern Segment is found. The easternmost boundary for semi-penetrative, spaced Sveconorwegian deformation is usually referred to as the Sveconorwegian Frontal Deformation Zone, whereas the Protogine Zone marks the transition from foliated, gneissic TIB rocks to migmatized gneisses of unrecognizable protoliths (e.g. Wahlgren et al. 1994; Andréasson & Dallmeyer 1995). The Protogine Zone has repeatedly been reactivated and its characteristics are somewhat different south

and north of lake Vättern (e.g. Gorbatschev 1980). For example, the dip of the shear zones varies along its strike, but is often near-vertical south of lake Vättern (Gorbatschev 1980).

Methods

The methodological aspects are described in detail in respective papers, but in this section some general aspects are presented and discussed. In addition to the methods presented below, field work was carried out in three different field areas, (1) north of Habo and (2) from Axamo airport approximately 30 km to the NW on the western shore of lake Vättern; and (3) around Malmbäck on the eastern side of lake Vättern (Fig. 1). More detailed mapping was enabled in the Malmbäck area, thanks to a close collaboration with the Geological Survey of Sweden. Geological mapping provided information about emplacement processes, alteration, metamorphism and deformation of the rocks. Whole-rock analyses were carried out on crushed rock powder.

Microscopy and SEM-EDS analysis

Optical microscopy was used for the observation of microstructures and allowed for the identification of minerals that could not be observed in hand specimens. Very fine-grained or atypical minerals were further identified with the aid of scanning electron microscopy and energy dispersive x-ray spectroscopy (SEM-EDS) analysis. Cathodoluminescence (CL-) and backscattered electron (BSE-) imaging were used to reveal detailed internal microstructures of grains such as compositional zoning and overgrowths in zircon. EDS is the analytical technique used for the elemental analysis and chemical characterization of minerals.

Microstructures and mineral parageneses provide information about the emplacement mechanisms and metamorphic history of a rock. Primary textures are often obscured in metamorphic rocks, but secondary minerals and microstructures provide important information about the history of the rock. However, it is important to remember that microstructures and minerals of a metamorphic rock are the end-products of what may have been a complex history and one must be aware of possible alternative interpretations.

Geochemical analysis

Major elements were analyzed on whole-rock powders by x-ray fluorescence (XRD), inductively coupled plasma mass spectroscopy (ICP-MS) or inductively coupled plasma emission spectroscopy (ICP-ES). Major elements are used for the classification of rocks and for variation diagrams (along with trace elements), which are used to recognize geochemical processes, such as fractional crystallization, assimilation, partial melting, mixing and hydrothermal alteration.

Trace elements were analyzed by ICP-MS. These elements are often studied in groups and have become important for modern petrology because of the improved capability to discriminate between petrological processes compared to the major elements. Elements in a certain group have similar chemical properties and are also expected to show similar geochemical behavior. Deviations from the group behavior or systematic changes in behavior within a group are used as an indicator of different petrological processes.

Radiogenic isotopes are the daughter products of naturally radioactive isotopes (for example ^{147}Sm decays by alpha emission to produce ^{143}Nd with a half-life of 106 Ga, Lugmair & Marti 1978). These isotopes can be measured either in a specific mineral or in a whole rock bulk analysis and provide information about the age of geological processes.

U-Pb zircon dating

Dating a magmatic or metamorphic event requires that a mineral suitable for age determination has crystallised or recrystallised during the event of interest. It is also necessary that the isotope system in the mineral has remained closed to diffusion during any geological events after the formation (Dickin 1995). For an isotope system to remain closed, the system should have a closure temperature that is higher than temperature conditions succeeding the event. Few isotopic systems used for age determination have closure temperatures high enough to escape diffusion during cooling after high-grade metamorphism or re-heating during later events. However, diffusion of U, Pb and Th in crystalline zircon is very slow at temperatures below c. 900°C (Lee et al. 1997; Mezger & Krogstad 1997) and unless zircon is recrystallised or loses Pb in the near-surface environment, its U-Pb-Th system remains undisturbed after crystallisation.

Recrystallisation may take place during partial melting, where zircon is partially dissolved and re-precipitated as secondary zircon. Secondary zircon normally occurs as U-rich (i.e. with low Th/U ratios), unzoned, CL-dark overgrowths which may be discordant to the igneous domain. Igneous zircon is usually subhedral to euhedral, commonly between 20 and 250 µm long and exhibits well-developed growth zoning. Zircon xenocrysts sometimes survive in a melt, especially if the melt is zircon-saturated, and may appear as inherited, zoned or homogeneous magmatic cores (that may be rounded, broken etc.) within the igneous domains (e.g. Hoskin & Schaltegger 2003; Corfu et al. 2003 and references in these publications).

Ion microprobe spot dating combined with CL- and BSE- imaging were used for the direct dating of different age domains in complex zircon.

Sm-Nd whole rock model ages

The Sm-Nd system offers the advantage of a simple chemical fractionation step between continental material and the mantle, it reveals the original time of crust-mantle separation and is known to be largely unaffected by later thermal and orogenic reworking (e.g. DePaolo et al. 1991). T_{CHUR} ages provide crustal residence ages, assuming that the material originated from a source of chondritic composition (Chondritic Uniform Reservoir or CHUR of DePaolo & Wasserburg 1976). T_{DM} ages represent approximate crustal residence ages, assuming that the rock was derived from mantle material following the depleted mantle curve of DePaolo (1981).

The best way to recognize juvenile continental crust is with Nd isotopes. Rocks with relatively high Sm/Nd ratios ("LREE-depleted") develop higher isotope ratios and positive ε_{Nd} values, whereas rocks with relatively low Sm/Nd ratios (LREE-enriched) develop lower isotope ratios, meaning that enriched sources like continental crust yield lower initial $^{143}Nd/^{144}Nd$ and hence negative ε_{Nd} values. However, because whole-rock Nd isotope data may represent the final product of a mixing process, possible end-members involved must be considered.

Whole-rock Sm-Nd isotope data were determined by thermal ionization mass spectrometry (TIMS).

Summary of papers

Paper I

Appelquist, K., Cornell, D. & Brander, L., 2008. Age, tectonic setting and petrogenesis of the Habo Volcanic Suite: Evidence for an active continental margin setting for the Transscandinavian Igneous Belt. GFF 130, 123-138.

The Habo Volcanic Suite (Fig. 2) is situated between shear zones of the Protogine Zone and has been intruded by a TIB granite, in Paper I dated at 1660±9 Ma. Larson & Berglund (1995) reported a preliminary U-Pb zircon TIMS crystallization age for the Habo Volcanic Suite at c. 1760 Ma. However, in Paper I careful CL- and BSE-zircon imaging, before U-Pb ion microprobe analyses of the same suite, were used to reveal magmatic as well as metamorphic zircon domains. These domains were dated at 1795±13 Ma and 1694±7 Ma, respectively. Hence, the previously reported age for the Habo Volcanic Suite reflect mixing between magmatic and metamorphic domains and the true magmatic age is set at 1795±13 Ma. This makes it part of the TIB-1 generation, whereas the 1694±7 Ma age is considered to reflect a thermal event related to the intrusions of younger TIB-2 rocks.

The Habo Volcanic Suite consists mainly of intermediate to basaltic compositions, and comprises pyroclastic and syn-eruptive volcaniclastic or volcanogenic sedimentary deposits. An active continental margin setting is suggested for the Habo Volcanic Suite as well as the Småland-Värmland part of the TIB. Two geochemically different groups of the Habo Volcanic Suite are distinguished. The first consists of primitive, alkaline mafic rocks and these rocks were used for the interpretation of the tectonic setting. The second group comprises felsic to intermediate, subalkaline compositions and is suggested to have formed by mixing or crustal assimilation between a juvenile basaltic magma (the first group) and an upper-crustal component.
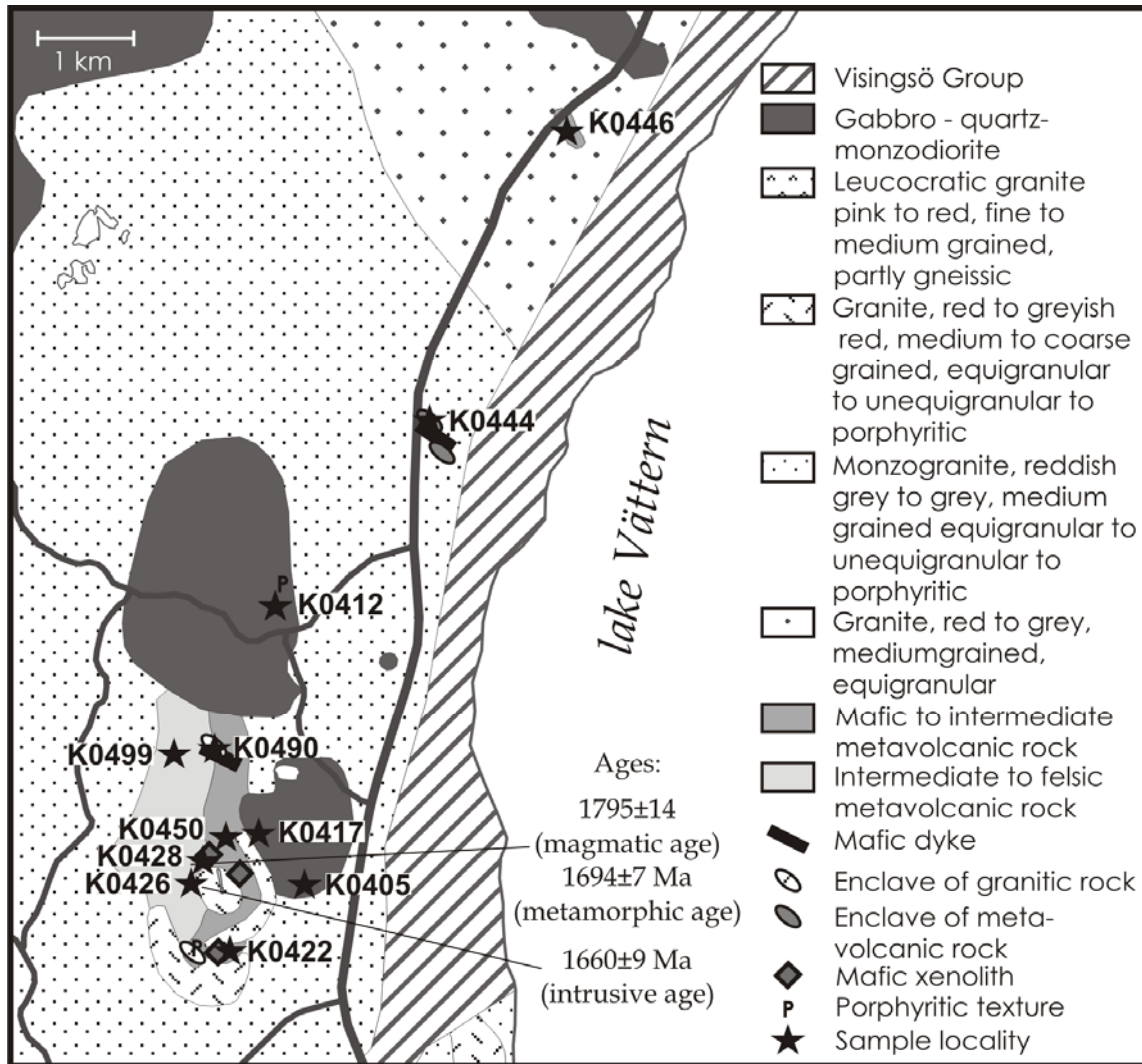
Fig. 2. Simplified geological map of the Habo Volcanic Suite (from Paper I).

Paper II

Appelquist, K., Eliasson, T., Bergström, U. & Rimša, A., 2009. The Palaeoproterozoic Malmbäck Formation in S Sweden: age, composition and tectonic setting. GFF 131, 229-243.

Because of their proximity to the Oskarshamn-Jönköping Belt and their substantial content of intermediate to basaltic lithologies, the Malmbäck Formation has previously been grouped together with so-called "pre-TIB rocks" (e.g. Magnusson 1958; Persson & Wikman 1986) and later with the Oskarshamn-Jönköping Belt (Mansfeld 1996; Mansfeld et al. 2005).

However, geological mapping indicated a correlation with the 1795 Ma Habo Volcanic Suite. This was confirmed by U-Pb SIMS dating of zircon from a rhyolite of the Malmbäck Formation, which yielded a magmatic age of 1796±7 Ma. Thus, the Malmbäck Formation is part of the TIB-1 rocks. Geological mapping revealed that the area includes one of the largest known volumes of mafic volcanic rocks within the TIB-1. Further, the Malmbäck Formation occurs as xenoliths and mega-xenoliths within plutonic TIB-1 rocks of the Småland-Värmland Belt of the TIB (Fig. 3, Table 1) comprising mafic to felsic volcanic rocks and syn-eruptive volcaniclastic and volcanogenic sedimentary deposits.
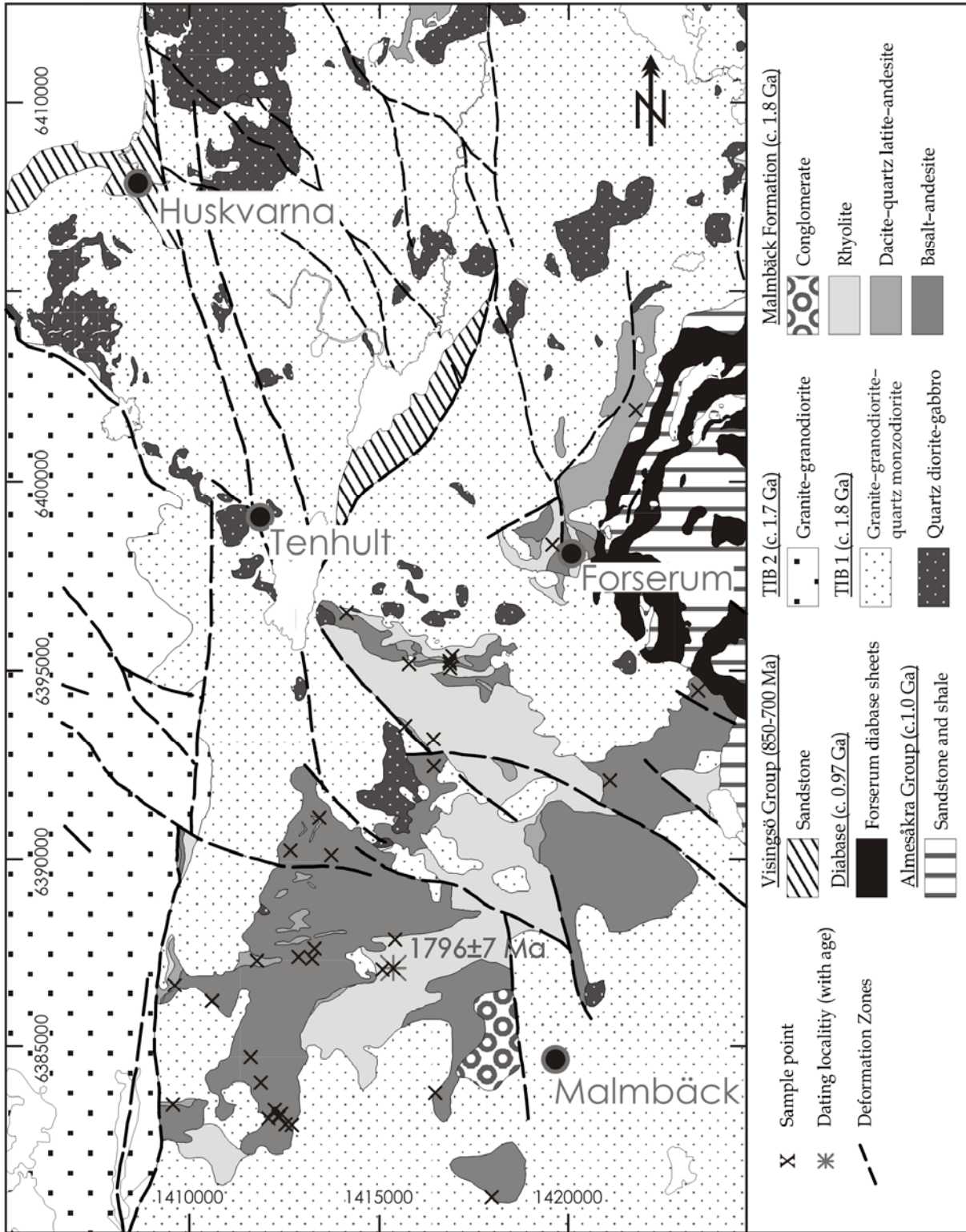
Fig. 3. Schematic bedrock map of the Malmbäck Formation, with sample localities and age of the dated rhyolite (modified from Paper II).

Geochemical signatures indicate emplacement in an Andean type active continental margin setting. Field observations and geochemical data indicate a close temporal and petrogenetic connection between the intrusive and extrusive rocks in the Malmbäck area and it is suggested that the volcanic rocks are

supracrustal analogues of the surrounding granitoids and gabbroids. Further, the co-existence of the volcanic and the plutonic rocks at the same crustal level is explained by stoping, the process whereby pieces of brittle country rock are engulfed by magma in a shallow crustal environment.

Paper III

Appelquist, K. & Johansson, Å. Nd isotope systematics of 1.8 Ga volcanic rocks within the Transscandinavian Igneous Belt, southcentral Sweden. Submitted to GFF.

In Paper I mixing or crustal assimilation between a juvenile basaltic magma and an upper-crustal component is envisaged to have formed the felsic-intermediate components of the Habo Volcanic Suite. In Paper II it is suggested that the Habo Volcanic Suite and the Malmbäck Formation are correlated in time and by emplacement mechanisms. The general trends of the variation diagrams for the Habo Volcanic Suite and the Malmbäck Formation are similar for most elements. Hence, in Paper III the objective was to test whether the two suites were formed by the same processes. Since radiogenic isotopes are insensitive to fractionation processes compared to major and trace elements, and are largely unaffected by later thermal and orogenic reworking, this theory was tested by analyzing Sm-Nd isotopes on a number of samples from the two suites. The second purpose of Paper III was to test whether the TIB-1 volcanic rocks were derived from the same type of source as Svecofennian and TIB-1 plutonic rocks.

The results imply that the basalts were derived from mildly depleted mantle-derived magmas with initial ε_{Nd} values of approximately +1 to +2, similar for those reported for many mafic plutonic TIB and Svecofennian rocks in the region. Nd isotope data of the felsic-intermediate members allows them to be mixing products of basalt and pre-existing juvenile crust, but the limited variation in initial isotope ratios in combination with the small number of analyses from each locality make it difficult to draw any firm conclusions.

Paper IV

Brander, L., Appelquist, K., Cornell, D. & Andersson, U.B. 1.71-1.60 Ga crust formation and 1.46-1.40 Ga Hallandian-Danopolonian deformation of Transscandinavian Igneous Belt-rocks of the Eastern Segment. Manuscript.

Paper IV presents a geochronological study of variably deformed granitoids (sensu lato), west of the city of Jönköping, just south of lake Vättern (Fig. 4). The granitoids range from deformed rocks of clear TIB-affinity in the east to strongly deformed gneisses of less obvious protoliths in the west. The aim of Paper IV was to investigate whether the southern Eastern Segment constitutes reworked rocks from the Transscandinavian Igneous Belt (TIB). Twenty granitoids were dated by U-Pb zircon ion probe analyses and 17 of these have distinct magmatic TIB-2 ages in the range 1.71-1.66 Ga, although 1.66-1.60 Ga Pb-Pb ages suggest a prolonged magmatic activity.

U-Pb zircon rim analyses also revealed that Hallandian - Danopolonian metamorphism took place at 1.46-1.40 Ga, in the thoroughly reworked rocks in the west as well as in the deformed TIB-rocks in the east. Leucosome formation for two samples was dated at 1443±9 Ma and 1437±6 Ma. However, no Sveconorwegian ages were found and it is suggested that the leucosome formation, the NW-SE to E-W folding as well as the NW-SE to E-W penetrative foliation and lineation in the investigated area were produced during the Hallandian-Danopolonian orogeny.

An aplitic dyke cross-cutting NW-SE folding and leucosome formation of a migmatite at Vråna has previously
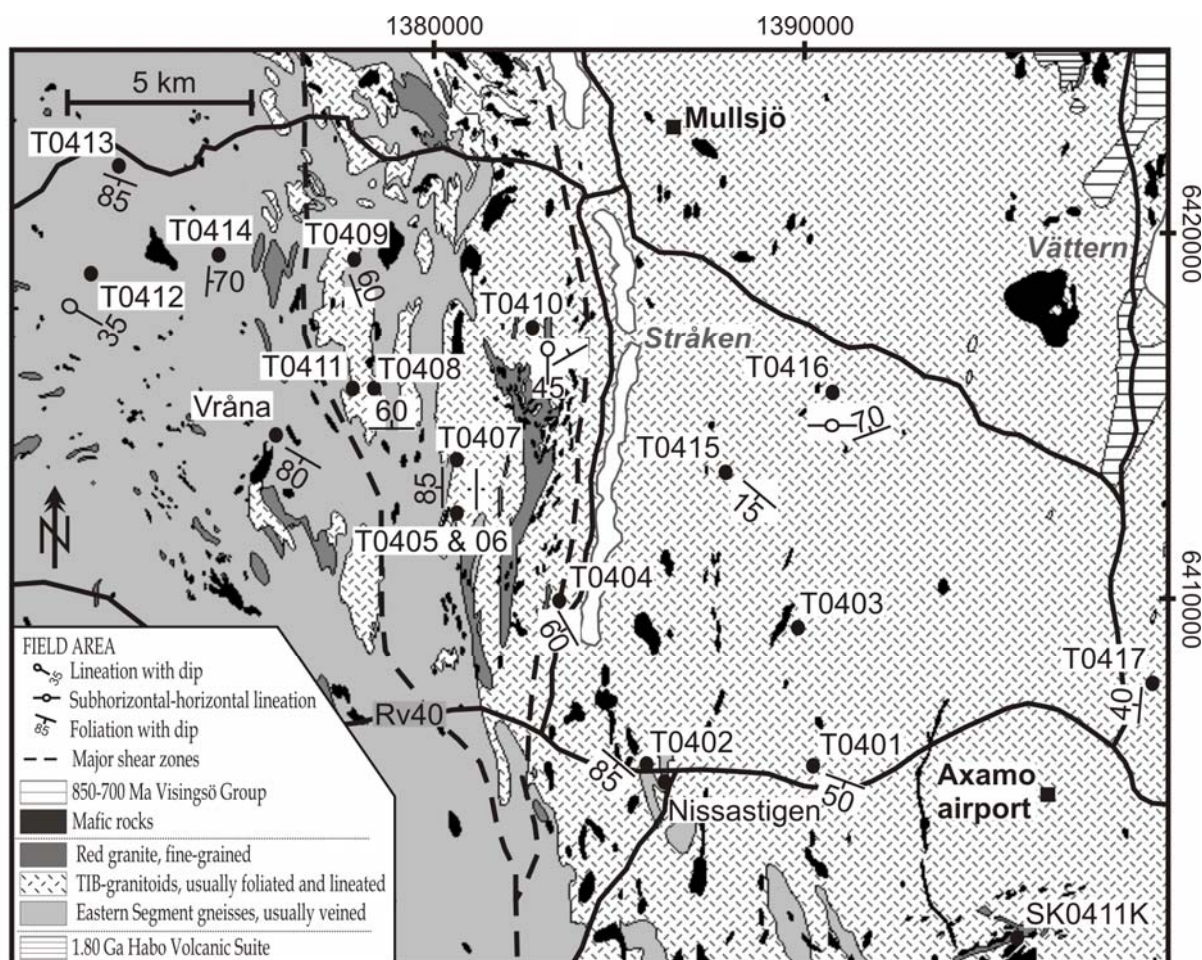
Fig. 4. Simplified geological map SW of lake Vättern, where the rock samples of Paper IV and V were collected. Modified after Larson & Berglund (1995). Circles mark sample localities. Rv40 = national road 40.

been dated at 1457±7 Ma, using the U-Pb zircon TIMS method (Connelly et al. 1996). In Paper IV this dyke was dated, using the U-Pb zircon ion probe method, at 1383±4 Ma. The latter age is more likely to represent the "true" emplacement age, as discussed in Paper IV, and sets a minimum age for the NW-SE folding in the investigated part of the Eastern Segment.

Paper V

Appelquist, K., Brander, L., Johansson, Å., Andersson, U.B. & Cornell, D. Geochemical and Sm-Nd isotope signatures of granitoids from the Transscandinavian Igneous Belt and the Eastern Segment of Sweden. Submitted to Geological Journal.

In Paper V we present geochemical data for eighteen granitoids of different metamorphic character and Sm-Nd whole-rock isotope data for eleven granitoids in the border zone between the TIB and the Eastern Segment (Fig. 4). These data give information on the type of magma and possible magma sources, as well as tectonic environment during emplacement. In Paper IV it was concluded that the emplacement ages for the granitoids of the southern Eastern Segment and the westernmost TIB are similar and that the Eastern Segment most probably consists of reworked TIB-rocks. If the Eastern Segment consists of reworked TIB-rocks, Nd-isotopic and geochemical signatures should be similar

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across the border zone. Hence, the aim of Paper V was to (1) provide evidence for the interpretation of the paleotectonic setting and evolution of the area during the time of emplacement of these granitoids; and (2) to test whether there are any differences in source composition between the western part of the TIB and the eastern part of the Eastern Segment.

Geochemical and isotopic signatures proved to be similar (cf. Fig. 5), supporting the idea that the TIB and the Eastern Segment originated from the same type of source and experienced the same type of emplacement mechanisms. High-K calc-alkaline to shoshonitic trends along with REE, spider and discriminant diagrams also support the conclusions of Paper I and II that the TIB was emplaced in an active continental margin setting. Nd isotope data are completely overlapping along the transect, with initial ε_{Nd} values in the range +0.3 to +2.6, suggesting that the TIB-2 granitoids were derived from a relatively juvenile pre-existing crustal source.

Synthesis: 1.8-1.4 Ga crustal evolution in southcentral Fennoscandia

TIB-1 volcanism

At c. 1.80 Ga, felsic to mafic volcanic rocks and their syn-eruptive volcaniclastic and volcanogenic sedimentary counterparts, were deposited in the southern part of TIB (Fig. 1, Table 1). The age determinations in Paper I and II demonstrate that the Malmbäck Formation and the Habo Volcanic Suite are indeed part of the TIB-1 magmatic suite. These rock suites also stand out from other southerly TIB-volcanic rocks as two of the few suites with primarily intermediate to basic compositions.

Field observations indicate that these rocks are composed mainly of terrestrial deposits with massive to highly vesicular lavas, ignimbrites, ashes, redeposited volcanic rocks and conglomerates (Paper I & II). Whereas the Habo Volcanic Suite (Paper I) lacks primary volcanic microtextures and has been metamorphosed at up to amphibolite-facies, the Malmbäck Formation (Paper II) comprises fairly well preserved volcanic rocks, although mineral assemblages suggest metamorphism at up to epidote-amphibolite facies in some areas. In the Dalarna region (D, Fig. 1), TIB-1 volcanic rocks were also deposited and in those rocks original structures and textures are generally preserved without any overprinting penetrative deformation (Nyström 2004).

Mafic volcanic rocks are the most suitable rocks for identifying the tectonic setting of ancient geological domains. Hence, the mafic-intermediate parts of the two volcanic suites enabled geochemical interpretations about the tectonic setting of the southern TIB. The mafic TIB-1 volcanic rocks, in the investigated areas, represent primitive rocks derived from a mildly depleted mantle (Paper I & III), whereas mixing or crustal assimilation between basalt magma and an upper-crustal component is likely to have formed the intermediate-felsic parts (Paper I & III). It is suggested that the TIB-1 volcanic rocks were emplaced in an active continental margin setting. The TIB regime was probably complex, similar to what is seen in the Andes today (e.g. Pitcher et al. 1985; and references therein) and is likely to have consisted of different regions characterised by subduction-related magmatism, Andinotype extension as well as local compression (Paper I & II).

TIB-1 plutonism

A south- to southwestward younging of protolith ages for the TIB-1 rocks suggests an active continental margin setting characterized by northward to

northeastward subduction (e.g. Andersson 1991; Andersson et al. 2004a).

TIB-1 granitoids and gabbros (1.81-1.76 Ga; Table 1 for references) were emplaced into the crust slightly after the volcanic rocks. The supracrustal TIB-1 rocks mainly occur as xenoliths and mega-xenoliths within the TIB-1 plutonic rocks and the main part of the volcanic rocks is also considered to be coeval with or slightly older than the surrounding TIB granitoids (Table 1), suggesting a co-magmatic relationship between the intrusive and extrusive TIB-1 rocks (e.g. Persson 1989; Paper I & II). The co-existence of volcanic and the plutonic rocks at the same crustal level is explained by stoping (Paper II), the process whereby blocks of brittle country rock are engulfed by magma in a shallow crustal environment (Best 2003). Fine-grained equigranular granitoids are also common in the region (cf. Wik et al. 2005a) and some of the plutonic rocks are likely to be subvolcanic intrusions.

In general, the mafic TIB plutonic rocks, of all ages, show typical arc-like patterns in geochemical spider diagrams and discrimination diagrams (e.g. Andersson & Wikström 2004; Andersson et al. 2004b; Rutanen & Andersson 2009). Mafic TIB rocks generally yield mildly depleted initial ε_{Nd} values, although data range between -0.4 and +3.6 (Fig. 5). This indicates that depleted mantle wedge material was enriched by fluids or melts from a subducting slab (e.g. Rutanen & Andersson 2009). The TIB-1 granitoids show a wide range of initial ε_{Nd} values, from -2.8 (if the Revsund granitoids of northcentral Sweden is included; Patchett et al. 1987; Andersson et al. 2002b) to +2.3 (Fig 5), and are interpreted as derived from the reworking of Svecofennian or TIB-0 crust (cf. Patchett et al. 1987; Andersson 1997a; Andersson & Wikström 2004). However, generating the granitoids by melting probably involved mafic underplating and the spread in initial ε_{Nd} values most likely

represents different degrees of partial melting, different mixing proportions between depleted mantle wedge material and pre-existing crust, or differences in the type of crust that was involved.

Three main types of TIB-1 granitoids have been observed in the investigated areas: fine-grained equigranular granites which are difficult to distinguish from the volcanic rocks and probably represent subvolcanic intrusions (see above), red to greyish red, alkali-calcic, normally equigranular granites of the Växjö type and reddish grey to dark grey, calc-alkaline, unequigranular to porphyritic Filipstad type monzogranites to quartz monzodiorites. The latter type includes numerous small gabbroic lenses and enclaves, and shows many examples of hybridization between the mafic and granitic components. Geochemically, the Växjö type granites are analogous to the rhyolites of the Malmbäck Formation (Paper II). The TIB gabbroic rocks are geochemically very similar to the volcanic andesites and basalts (cf. Paper I, II & V). However, it is unclear if the intermediate dacites to andesites are supracrustal analogues of the Filipstad type granitoids (Paper II).

TIB-2 volcanism

After a magmatic hiatus between 1.75 and 1.72 Ga, accretionary growth of the Fennoscandian Shield continued west to southwestwards between 1.71 and 1.55 Ga (cf. compilation in Bingen et al. 2008a; Paper IV). Volcanic rocks belonging to the TIB-2 generation are lacking in the southern part of TIB, although mafic to felsic TIB-2 volcanic rocks are widespread in the Dalarna region (D, Fig. 1). In the Dalarna region, volcanic rocks formed both during the TIB-1 and the TIB-2 magmatic events (Lundqvist & Persson 1996, 1999). Burial metamorphic patterns, with metamorphic grades ranging from
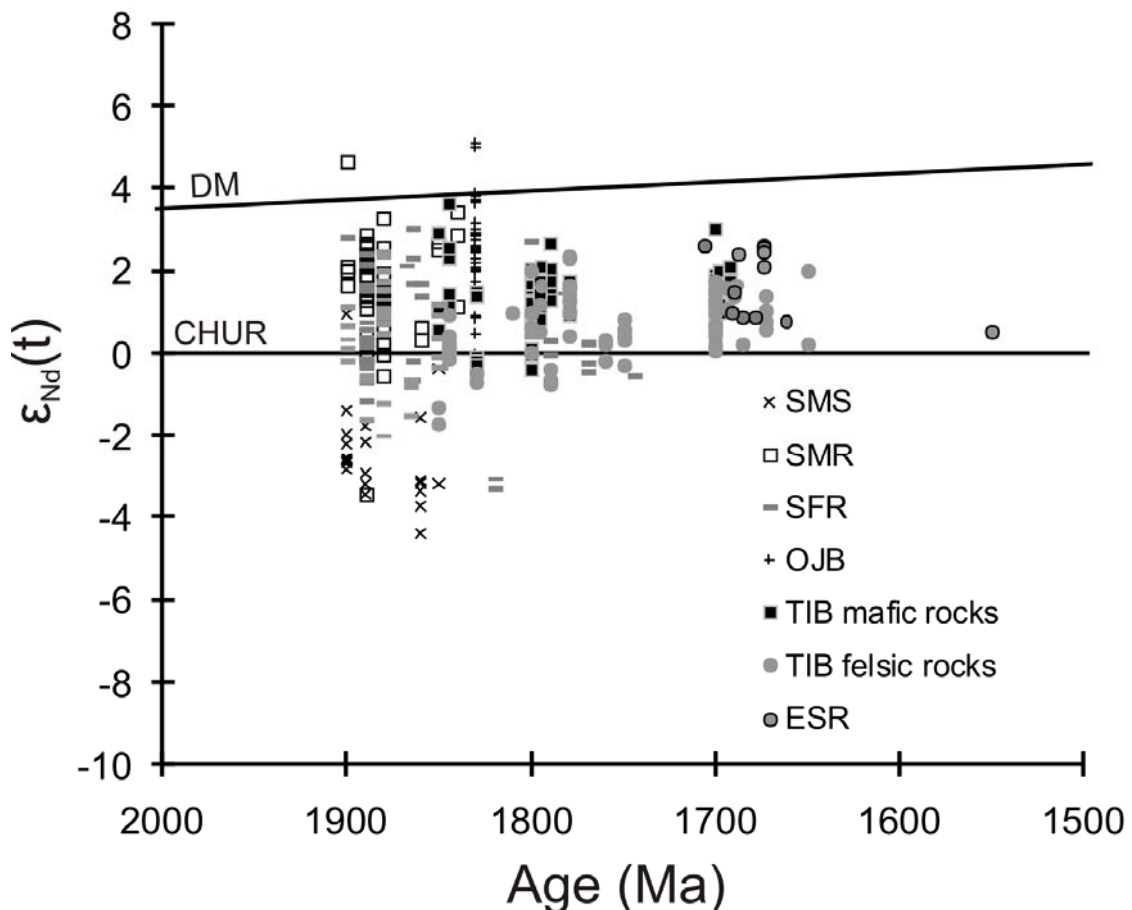
Fig. 5. ε_{Nd} vs. Age diagram for rocks of the southern Fennoscandian Shield. DM: Depleted Mantle, CHUR: Condritic Uniform Reservoir, SMS: Metasediments of the Svecofennian Domain; SMR: Svecofennian mafic rocks; SFR: Svecofennian felsic rocks; OJB: Oskarshamn-Jönköping Belt; TIB: Transscandinavian Igneous Belt; ESR: Eastern Segment rocks.

DM evolution line from DePaolo 1981. SMS from Patchett et al. (1987); Kumpulainen et al. (1996); Andersson (1997a); Andersson (1997b); Andersson et al. (2002b); Högdahl et al. (2008). SMR from Wilson et al. (1985); Patchett et al. (1987); Valbracht (1991a); Björklund & Claesson (1992); Kumpulainen et al. (1996); Andersson (1997a); Högdahl et al. (2008); Rutanen & Andersson, (2009). SFR from Wilson et al. (1985); Patchett et al. (1987); Valbracht (1991b); Kumpulainen et al. (1996); Andersson (1997a); Andersson (1997b); Andersson et al. (2002b). OJB (including the Fröderyd Group) from Mansfeld et al. 2005. TIB-0 mafic rocks from Andersson (1997a), but TVZ rocks recalculated at 1845 and Tiveden rocks at 1830 Ma; Claeson & Andersson (2000). TIB-0 felsic rocks from Andersson (1997a), but TVZ rocks recalculated at 1845 and Tiveden rocks at 1830 Ma; Claeson & Andersson (2000); Wikström & Andersson (2004). TIB-1 mafic rocks from Johansson & Larsen (1989), recalculated at 1800 Ma (cf. Johansson et al. 2006); Andersson (1997a); Andersson et al. (2007); Rutanen & Andersson (2009); Paper III. TIB-1 felsic rocks from Wilson et al. (1985); Patchett et al. (1987); Johansson & Larsen (1989), but recalculated at 1760 Ma (cf. Johansson et al. 2006); Andersson (1997a); Andersson et al. (2002b); Wikström & Andersson (2004); Johansson et al. (2006); Paper III. TIB-2 mafic rocks from Wilson et al. (1985); Nyström (1999); Claeson (2001). TIB-2 felsic rocks from Wilson et al. (1985); Patchett et al. (1987); Heim et al. (1996); Nyström (1999); Paper V. ESR from Persson et al. (1995); Lindh (1996); Paper V.

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greenschist to prehnite-pumpellyite, indicate that these rocks were not buried as deeply as the TIB-1 Småland volcanic rocks. However, the lack of zeolite facies rocks, as well as a regional unconformity at the top of the sequence, suggests that the original thickness of the Dala sequence was thousands of meters thicker than today (Nyström 2004).

TIB-2 plutonism

Between 1.71 and 1.65 Ga TIB-2 granitoids and gabbros were emplaced mainly west of the TIB-1 rocks (Paper I, IV & V). The onset of the TIB-2 magmatism was characterized by an east- to northeastward directed subduction environment (e.g. Andersson et al. 2004a). A major part of the TIB-2 granitoids, in the southern part of the Fennoscandian Shield, is constituted by greyish to red, coarse-grained granitoids with granular K-feldspar megacrysts, sometimes referred to as Barnarp-type granites. These rocks may be traced into the interior of the southern Eastern Segment, as indicated by recent mapping by the Geological Survey of Sweden (pers. comm. Lena Lundqvist). The results of Paper IV and V, showing similar geochemical and isotopic signatures for the TIB and the Eastern Segment of the Southwest Scandinavian Domain, support the theory that the Eastern Segment is the metamorphosed counterpart of the TIB-2 (cf. Lindh & Gorbatschev 1984; Lindh & Persson 1990; Wahlgren et al. 1994; Connelly et al. 1996; Berglund et al. 1997; Söderlund et al. 1999; Åhäll & Larson 2000; Andersson 2001; Söderlund et al. 2002; Söderlund et al. 2004a).

Whereas the initial ε_{Nd} values and the ε_{Nd} evolutionary lines of the TIB-1 granitoids overlap with those of Svecofennian and TIB-0 felsic rocks, the TIB-2 granitoids (including those of the Eastern Segment) have yielded somewhat higher initial ε_{Nd} evolutionary lines (Fig. 6). These rocks were probably derived by reworking of a juvenile crustal source, such as the rocks of the Oskarshamn-Jönköping Belt (Paper V).

Although the samples of this study cover a restricted area, previously published initial ε_{Nd} values from the southern part of the Fennoscandian Shield overlap with the data presented in this thesis (Fig. 5), suggesting that our interpretations may be applicable to the relatively undeformed TIB-2 granitoids in the southernmost part of the Fennoscandian Shield as well as the granitoid gneisses within the southern part of the Eastern Segment.

It has previously been concluded that the southern Eastern Segment show geochemical similarities with the TIB (cf. Möller et al. 2005), although areas representing lower crustal sections of the southern Eastern Segment are more heterogeneous and show greater compositional varieties along with veining and banding (Wik et al. 2006). In spite of overlaps in U-Pb zircon ages, Nd-isotopes and geochemical signatures, a tendency to a more metaluminous and calc- alkaline character for the Eastern Segment gneisses is observed (Paper V), compared with the more alkali-calcic to alkalic and peraluminous character visible for the TIB granitoids presented in this thesis. This is probably coupled with a volcanic arc granite geochemical character for both areas, with a tendency for the TIB-2 granitoids to straddle the boundary to syn/late-collisional type granites (see figure 6 in Paper V). The geochemical data of Paper I, II and V overlaps that of other TIB-1 and TIB-2 data from the same general area, where the former tending to be somewhat more alkali-rich than the latter. Magma sources in the west thus tend to be more mafic and calcic, which may be explained by the idea that these parts represent deeper crustal sections and thus are poorer in SiO_2. This is due to ascending mafic magmas from the
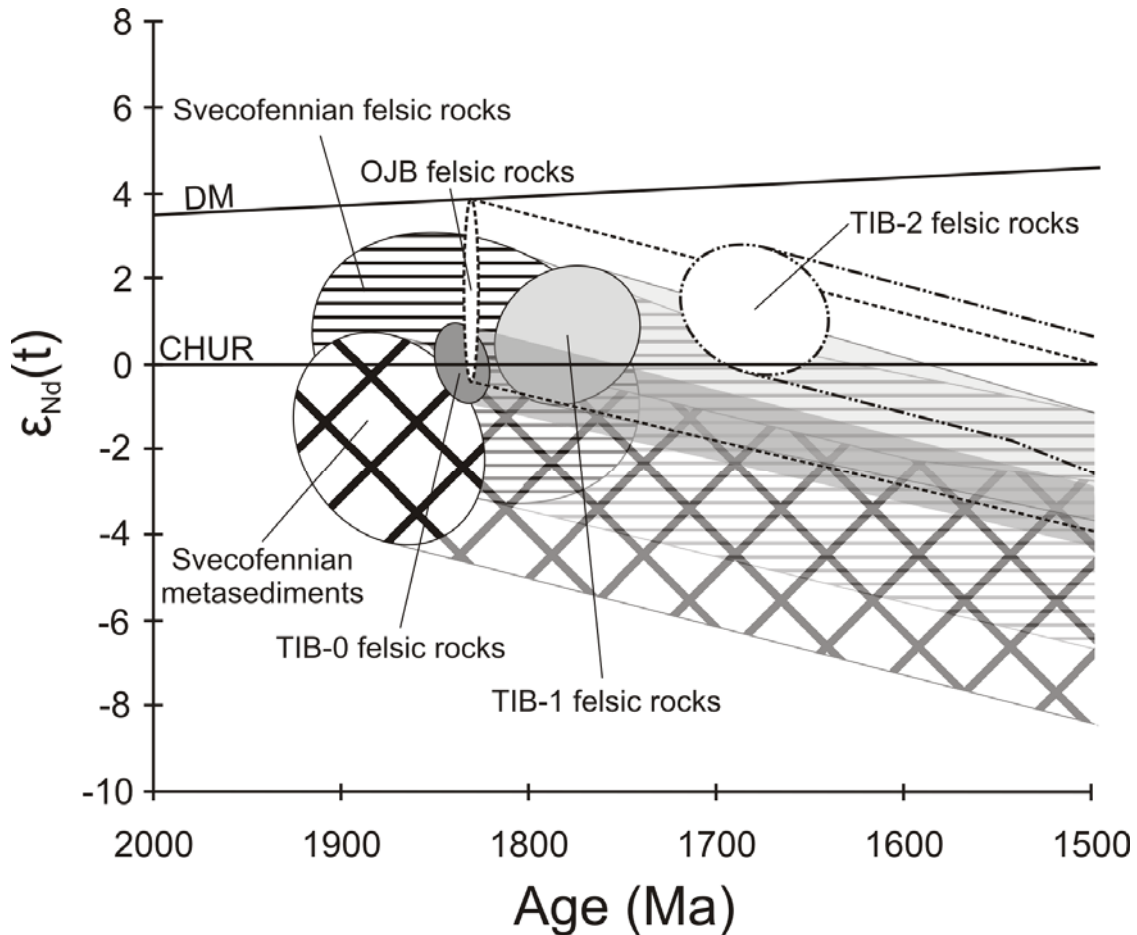
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Fig. 6. ε_{Nd} vs. Age diagram. Fields for initial ε_{Nd} values (ellipses) are plotted for TIB-2 felsic rocks (from the TIB and the Eastern Segment) and its possible source rocks in southern Fennoscandia. Fields from ellipses represent ε_{Nd} evolution lines. DM: Depleted Mantle, CHUR: Condritic Uniform Reservoir, TIB: Transscandinavian Igneous Belt; OJB: Oskarshamn-Jönköping Belt.

DM evolution line from DePaolo 1981. Svecofennian metasediments from Patchett et al. (1987); Kumpulainen et al. (1996); Andersson (1997a); Andersson (1997b); Andersson et al. (2002b); Högdahl et al. (2008). Svecofennian felsic rocks from Wilson et al. (1985); Patchett et al. (1987); Valbracht (1991b); Kumpulainen et al. (1996); Andersson (1997a); Andersson (1997b); Andersson et al. (2002b). TIB-0 felsic rocks from Andersson (1997a), but TVZ rocks recalculated at 1845 and Tiveden rocks at 1830 Ma; Claeson & Andersson (2000); Wikström & Andersson (2004). OJB felsic rocks from Mansfeld et al. 2005. TIB-1 felsic rocks from Wilson et al. (1985); Patchett et al. (1987); Johansson & Larsen (1989), but recalculated at 1760 Ma (cf. Johansson et al. 2006); Andersson (1997a); Andersson et al. (2002b); Wikström & Andersson (2004); Andersson et al. (2004c); Johansson et al. (2006), Paper III. TIB-2 felsic rocks from Persson et al. (1995); Heim et al. (1996); Lundqvist & Persson (1999); Nyström (1999); Paper V.

volatile-fluxed mantle wedge underplating the crust. In this process, heat is transferred to the already hot lower crust, causing partial melting and mixing between mafic magmas and the lower continental crust (cf. Condie 2005).

Hallandian-Danopolonian orogeny

Pronounced reworking affected the crust of the southern Eastern Segment of the Southwest Scandinavian Domain and the western part of the southern TIB during the 1.47-1.40 Ga Hallandian-Danopolonian orogeny (cf. Hubbard 1975; Christoffel et al.

1999; Söderlund et al. 2002; Austin Hegardt et al. 2005; Möller et al. 2007; Brander & Söderlund 2009; Paper IV). The term Hallandian was first introduced by Hubbard (1975), who proposed the term for granite-monzonite magmatism and associated metamorphism in the Eastern Segment. This metamorphism was, however, later dated as Sveconorwegian (Johansson et al. 1991).

Christoffel et al. (1999) and Söderlund et al. (2002) referred to the Hallandian as a 1.46-1.42 Ga *thermo-magmatic event* affecting the Eastern Segment, but Söderlund et al. (2002) stressed that the term was not necessarily linked to an orogenic event. Christoffel et al. (1999) dated (1) metamorphic zircon growth in a mafic gneiss at 1.44 Ga, (2) irregular 1.43-1.40 Ga granitic dykes cross-cutting the gneissosity in the host rock and (3) the crystallization of the Varberg Charnockite-Granite Association at 1.40 Ga in the Halmstad-Varberg region in the southwestern part of the Eastern Segment (Fig. 7). Söderlund et al. (2002) also dated complex zircon in variably reworked and veined orthogneisses east of Varberg and concluded that the emplacement of dykes and formation of secondary zircon at 1.46-1.40 Ga is relatively widespread in the Eastern Segment. They also discussed whether the Hallandian event was associated with a regional penetrative deformation, but argued that the characterization of the Hallandian event required further investigations. Austin Hegardt et al. (2005) dated 1.43 and 1.44 Ga zircon rims at the Viared locality, inside the southern Eastern Segment (Fig. 7), which they ascribed to a regional migmatization. At the Högabjär locality, in the western part of the southern Eastern Segment, Möller et al. (2007) dated the leucosome of a migmatitic gneiss at 1.43 Ga. Further, Connelly et al. (1996) reported c. 1.47 Ga zircon and

titanite growth at the Vistbergen locality in the southern Eastern Segment (Fig. 7).

Outside the Southwest Scandinavian Domain, Bogdanova et al. (2001) reported 1.49-1.45 Ga $^{40}Ar/^{39}Ar$ hornblende ages from drill cores in Lithuania, which they related to E-W trending zones of crustal shearing. Bogdanova (2001) introduced the term Danopolonian orogeny, reflected by the c. 1.55-1.45 Ga anorthosite-mangerite-charnockite(-rapakivi)-granite magmatic activity and associated tectonism in the western part of the East European Craton. Čečys & Benn (2007) also linked c. 1.45 Ga syn-kinematic emplacements of granitoids in the Blekinge Province, on the Danish island of Bornholm, and in Lithuania to the Danopolonian orogeny. Further, Johansson et al. (2006) dated thin metamorphic zircon overgrowths and resetting of the U-Pb system in titanite in the Blekinge Province at 1.45 to 1.40 Ga, which they ascribed to a regional tectonothermal event. In a review by Brander & Söderlund (2009) they emphasize the widespread 1.47-1.44 Ga magmatic activity in the interior of the Fennoscandian Shield. They stressed that the magmatism largely coincides in age with the high-grade metamorphism in SW Sweden and suggested an orogenic connection.

The relationship between the Hallandian and Danopolonian events and whether the two can be grouped together into a "Hallandian-Danopolonian" orogeny has been discussed by e.g. Bingen et al. (2008b). They emphasized that the significance of the Hallandian-Danopolonian as a large scale orogenic event is difficult to assess, but that it may be related to (1) a collision, (2) reworking of the south to southwestern margin of Fennoscandia, or (3) to a change in subduction geometry in an active margin setting. However, to avoid confusion, and because it is most likely that the Hallandian and the Danopolonian orogenies represent

Table 1. Age determinations reflecting the tectonic evolution of S Sweden (within the southern part of Fennoscandia).

Event	Age (Ga)[1]	Region[2]	Expressed as	References
Post-orogenic magmatism	0.93 (zr)	S. ES	Post-kinematic pegmatite	Söderlund et al. 2008
	0.93-0.95 (mz & ti)	S. ES	Data indicating slow cooling attributed to late-stage erosion and isostatic uplift	Christoffel et al. 1999
	0.95-0.96 (zr)	S. ES	Post-kinematic dykes	Andersson et al. 1999; Christoffel et al. 1999; Möller & Söderlund 1997; Möller et al. 2007; Söderlund et al. 2008
Sveconorwegian orogeny	*0.92-1.10*	*ES*	*Sveconorwegian continent-continent collision*	e.g. Bingen et al. 2008b
	0.92-0.96 (ti)	S. ES	Ti in grey gneiss, garnet amphibolite and titanite inclusions in garnet from eclogite	e.g. Johansson et al. 1993; Wang et al. 1998; Johansson et al. 2001
	0.93-0.96 (ti)	S. ES	Recrystallization event, either short-lived or near 600°C (closure T of ti)	Connelly et al. 1996; Austin Hegardt et al. 2005
	0.95-0.98 (bd)	S. ES	Blekinge-Dalarna dolerites (e.g. Karlshamn dolerite dyke)	Patchett et al. 1994; Söderlund et al. 2004b
	0.95-1.0 (zr)	S. ES	Partial melting (granitic veins)	Möller & Söderlund 1997; Andersson et al. 1999; Söderlund et al. 2008
	0.96-0.97 (zr)	S. ES	High-pressure eclogite facies metamorphism	Johansson et al. 2001
	0.96-0.98 (ti)	N. ES	Greenschist facies (east) to middle amphibolite facies (west) metamorphism	Söderlund et al. 1999
	0.96-0.98 (zr)	S. ES	High-pressure granulite facies metamorphism	e.g. Söderlund 1996; Wang et al. 1998; Söderlund et al. 2002; Andersson 2001; Andersson et al. 2002a; Möller et al. 2007
	0.97 (zr)	S. ES	Metamorphic zircon in pegmatite dyke	Söderlund 1996
	0.98 (zr)	S. ES	E-W folding and synchronous migmatization	Möller et al. 2007
	1.0 (zr)	PZ	Metamorphic zircon in mafic intrusions along PZ (1.0-1.2kbar, ~600°C)	Söderlund et al. 2004a
Extension-related magmatism	1.20 (ap, bd & zr)	PZ	Granitic, syenitic and mafic intrusions	Johansson 1990; Hansen & Lindh 1991; Jarl 2002; Söderlund & Ask 2006; Larsson & Söderlund 2005

	1.22 (zr)	PZ	Metamorphic zircon in mafic intrusions	Söderlund et al. 2004a
	1.22 (bd & zr)	PZ	Granitic, syenitic and mafic intrusions	e.g. Johansson 1990; Johansson & Johansson 1990; Ask 1996; Söderlund et al. 2004a; Söderlund et al. 2005; Söderlund & Ask 2006
	1.26-1.27 (bd & zr)	Dalarna-Västerbotten, Finland	Sill-like bodies of the Central Scandinavian Dolerite Group	Suominen 1991; Söderlund et al. 2004b; Söderlund et al. 2005
Post-(?) Hallandian-Danopolonian events	1.37-1.38 (ti)	W. TIB	Cooling through 550-650°C after a metamorphic event. Eastern limit of Sveconorwegian thermal effects?	Lundqvist 1996; **Paper IV**
	1.38 (zr)	C./S. ES	Vråna aplitic dyke cross-cutting folded migmatite	**Paper IV**
	1.38-1.40 (zr)	S. ES	Granite-monzonite magmatism (e.g. Tjärnesjö & Torpa granitoids)	Åhäll et al. 1997; Andersson et al. 1999; Christoffel et al. 1999
	1.39-1.41 (zr)	S. ES	Emplacement of pegmatite and granite dykes preceeding a deformational event	Söderlund 1996; Johansson et al. 2001; Möller et al. 2007
	1.39 (zr)	S. ES	Emplacement of granitic and pegmatitic dykes which cross-cut gneissosity in host rock	Christoffel et al. 1999
	c. 1.41 (zr)	W. TIB	Emplacement of the Axamo Dyke Swarm	Lundqvist 1996
Hallandian-Danopolonian orogeny (main deformation)	*c. 1.41-1.45*	S. ES & W. TIB	*Collisional event?*	Brander in prep.
		S. ES	NW-SE folding bracketed between 1.44 and 1.38 Ga	**Paper IV**
	1.41-1.45 (zr)	W. TIB	NW-SE to E-W penetrative foliation and lineation causing metamorphic zr rims in TIB-2 granitoids	**Paper IV**
	1.41-1.46 (zr)	S. ES	High-grade metamorphism (veining, leucosome formation and anatexis, recrystallization and new growth of zr)	Christoffel et al. 1999; Andersson 2001; Söderlund et al. 2002; Söderlund et al. 2004a; Austin Hegardt et al. 2005; Rimša et al. 2007; Möller et al. 2007; **Paper IV**
	1.42-1.45 (ti)	Blekinge	Resetting of ti in majority of Blekinge rocks	Johansson et al. 2006
	1.43-1.45 (ti)	Bornholm	Post-magmatic or post-metamorphic cooling	Zarinš & Johansson 2009
	1.44 (zr)	Blekinge	Metamorphic zr rims from coastal gneiss & migmatite paleosome	Johansson et al. 2006

Table 1 (cont.).

Event	Age (Ga)[1]	Region	Expressed as	References
Hallandian-Danopolonian orogeny (cont.)	1.44 (zr)	PZ	Metamorphic zircon in mafic intrusions	Söderlund et al. 2004a
Intra-cratonic magmatism (rel. to the Hallandian-Danopolonian orogeny)	1.44-1.47 (zr)	S. Fennoscandia (S. TIB, Bornholm & Lithuania)	Felsic intrusions	Cf. compilation in Brander & Söderlund 2009
	1.45-1.47 (bd)	Interior of Fennoscandian Shield (N. TIB & Svecofennian Province)	Anorthositic and gabbroic plutons	Brander & Söderlund 2009; and references therein
	1.45-1.48 (zr)	Bornholm	Protolith ages for granitoids and gneisses	Zariņš & Johansson 2009
	1.46-1.47 (bd & zr)	Interior of Fennoscandian Shield (ES, TIB & Svecofennian Province)	Emplacement of mafic dykes (NW to NE trending)	Welin 1994; Lundström et al. 2002; Söderlund et al. 2005; Brander & Söderlund 2009 and references within these publications
		→	Graben formation (NW-trending)	(cf. Brander & Söderlund 2009)
		→	Continental basalt eruptions	(cf. Brander & Söderlund 2009)
	1.47 (zr)	S. ES	Pegmatite dyke syn-emplaced at gneiss-forming event at Kullaberg peninsula?	Söderlund et al. 2008
Extension-related magmatism	1.56-1.57 (bd & zr)	PZ+SFDZ	Mafic intrusions (e.g. the Åker metabasite and other dolerite dykes)	e.g. Wahlgren et al. 1996; Söderlund et al. 2004a; Söderlund & Ask 2006
TIB-2 plutonism	1.65-1.71 (zr)	W. TIB	Granitoids and associated gabbroic plutonic rocks	cf. compilation in Åhäll & Larson 2000; **Paper IV**
	1.65-1.71 (zr)	N. ES	Granitoids and associated gabbroic plutonic rocks	cf. compilation in Söderlund et al. 1999; compilation in Bingen et al 2008b
	1.65-1.71 (zr)	S. ES	Granitoids and associated gabbroic plutonic rocks	cf. compilation in Söderlund et al. 1999; compilation in Bingen et al 2008b; **Paper IV**

	Age (Ga)[1]	Region[2]	Description	References
	1.68-1.70 (zr)	Dalarna	Granitoids and associated gabbroic plutonic rocks	Ahl et al. 1999
TIB-2 volcanism	c. 1.70 (zr)	Dalarna	Megaxenoliths of metavolcanic rocks in Värmland TIB-1 and TIB-2 granitoids, as well as basement of the Dala-Trysil sandstone.	Lundqvist & Persson 1999
			Emplaced in an extensional tectonic regime?	Ahl et al. 1999
TIB-1 plutonism	1.75-1.77 (zr)	Blekinge	Blekinge bedrock (meta-TIB)	Johansson et al. 2006
	1.76-1.80 (zr)	N. ES	Meta-TIB	cf. compilation in Söderlund et al. 1999
	1.76-1.81 (zr)	TIB	Granitoids and associated gabbroic rocks	e.g. compilation in Åhäll & Larson 2000; Högdahl et al. 2004
	c. 1.79 (zr)	Dalarna	Granitoids and associated gabbroic rocks	Ahl et al. 1999
	1.81 (zr)	Blekinge	Proto-crust?	Johansson et al. 2006
TIB-1 volcanism	1.76 (zr)	Blekinge	Metavolcanic rock	Johansson et al. 2006
	1.77-1.81 (zr)	S. TIB	Xenoliths of metavolcanic rocks within TIB-1 plutonic rocks	Wikman 1993; Wikström 1993; Mansfeld 1996; Nilsson & Wikman 1997; Persson & Wikman 1997; Söderlund & Rodhe 1998; Wik et al. 2005b; **Paper II**
	1.80 (zr)	SW. TIB	Xenoliths of metavolcanic rocks within TIB-2 plutonic rocks	**Paper I**
	c. 1.80 (zr)	Dalarna	Xenoliths of metavolcanic rocks within TIB-1 and TIB-2 plutonic rocks	Lundqvist & Persson 1999
TIB-0 plutonism	1.84-1.86 (mz, zr)	Interior of Fennoscandian Shield: along the SW border TIB - Svecofennian Province	Crystallization ages of granitoids	e.g. Persson & Wikström 1993; Wikström 1996; Claeson & Andersson 2000; Wikström & Persson 2002; Wik et al. 2005a

[1] Mineral used for age determination within paranthesis; ap: apatite, bd: baddeleyite, mz: monazite, ti: titanite, zr: zircon.

[2] C: Central, ES: Eastern Segment, N: Northern, PZ: Protogine Zone, S: Southern, SFDZ: Sveconorwegian Frontal deformational Zone, TIB: Transscandinavian Igneous Belt.

the same event, the term Hallandian-Danopolonian orogeny is preferred in this thesis.

As outlined above, migmatization during the Hallandian-Danopolonian orogeny was widespread in the southern Eastern Segment. In Paper IV, it is concluded that the leucosome formation and NW-SE to E-W folding in the northeastern part of the southern Eastern Segment (Fig. 7), as well as the NW-SE to E-W penetrative foliation and lineation in the southwestern TIB were produced during the 1.47-1.40 Ga Hallandian-Danopolonian orogeny. This is shown by 1.46-1.40 Ga metamorphic U-Pb zircon rim ages, from both the Eastern Segment and the westernmost TIB. Leucosome formation for two samples is dated at 1443±9 Ma and 1437±6 Ma (Paper IV). The 1437±6 Ma age for the migmatite at Vråna probably dates the regional migmatization, related to orogenic thickening of the Eastern Segment,
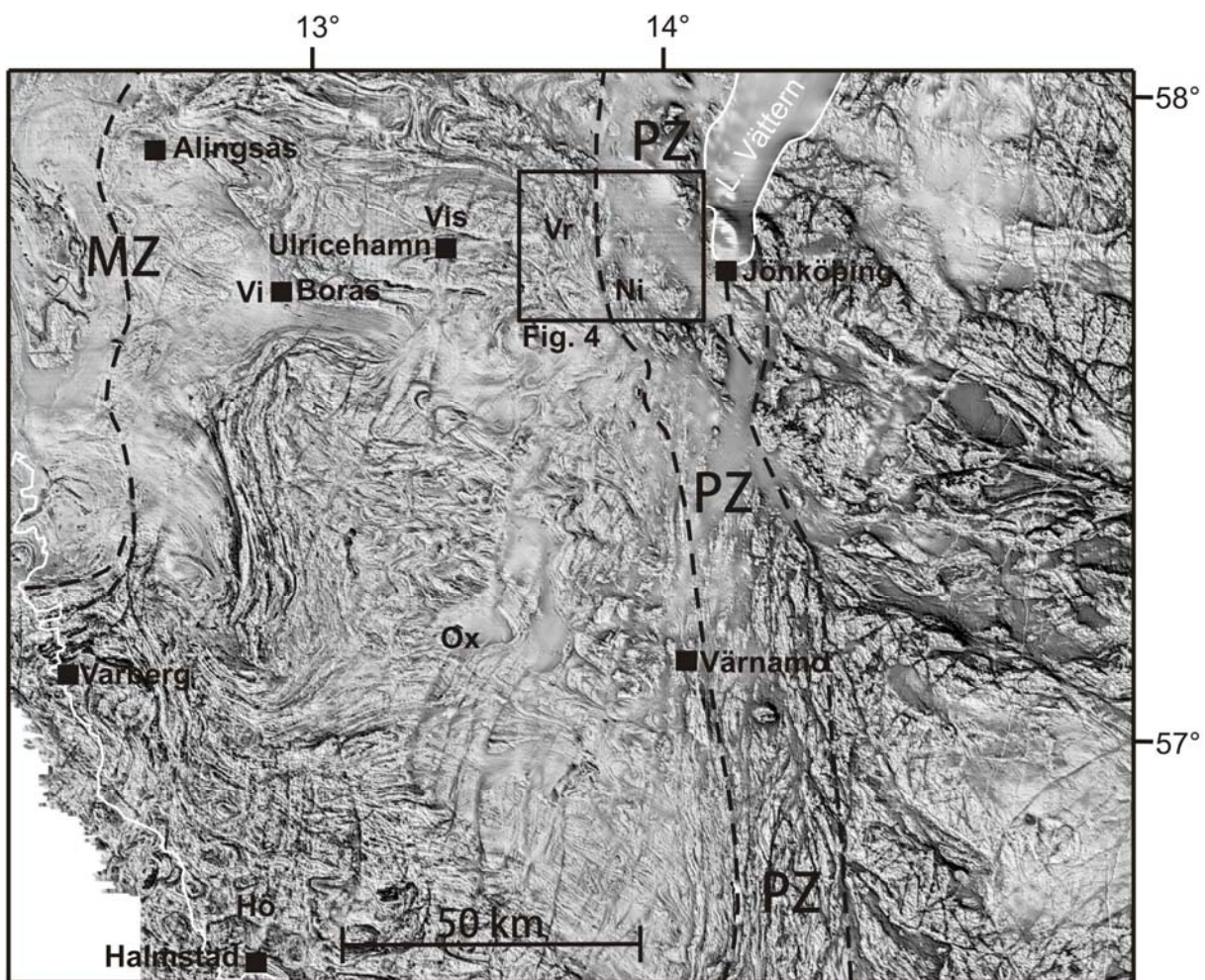

Fig. 7. Magnetic anomaly map of southcentral Sweden. White solid lines mark shore lines, black striped lines mark major shear zones, MZ = Mylonite Zone, PZ = Protogine Zone. The boundaries of the MZ are outlined after Koistinen et al. (2001) and the general boundaries of the PZ are outlined after Wik et al. (2006). The Eastern Segment is located approximately between the MZ and the western boundary of the PZ. Key localities Hö: Högabjär, Ni: Nissastigen, Ox: Oxanäset, Vi: Viared, Vis: Vistbergen, Vr: Vråna are discussed in the text. Box outlines the study area shown in Fig. 4. Magnetic anomaly map published with permission from the Geological Survey of Sweden ©Sveriges geologiska undersökning.

whereas the 1443±9 Ma age dates an injection migmatite, produced by heat from a gabbroic intrusion at Nissastigen. The injection migmatite at Nissastigen is however also considered to be a product of the Hallandian-Danopolonian orogeny, as the relationship to the widespread magmatism in Fennoscandia at 1.47-1.44 Ga is evident (cf. Table 1; Brander & Söderlund 2009 and references therein).

The minimum age of the NW-SE to E-W folding in the northeastern part of the southern Eastern Segment is determined by a 1383±4 Ma cross-cutting dyke at Vråna (Fig. 4 & 7; Paper IV). Regional NW-SE to E-W Hallandian-Danopolonian folding in the southern Eastern Segment would be in accordance with the theory that a continental block of unknown origin collided with the Fennoscandian Shield from southwest during a Hallandian-Danopolonian collisional event (Brander in prep.). Based on U-Pb titanite dates, it is further concluded that temperatures in the field area of Fig. 4 did not drop beneath c. 600°C until about 1.37 Ga (Lundqvist 1996; Paper IV).

Hypothesis regarding the late Proterozoic evolution in southcentral Fennoscandia

During the 1.10-0.92 Ga Sveconorwegian orogeny, the present-day Eastern Segment was subjected to amphibolite- to granulite, and in places eclogite facies metamorphism, migmatization and folding (e.g. Johansson et al. 1991; Connelly et al. 1996; Wang et al. 1996; Berglund et al. 1997; Andersson et al. 1999; Söderlund et al. 2002; Austin Hegardt et al. 2005; Möller et al. 2007). Möller et al. (2007) presented convincing evidence for 0.98 Ga Sveconorwegian migmatization and E-W folding at the Oxanäset locality in the interior of the southern Eastern Segment (Fig. 7). They concluded that the folding took

place in response to N-S shortening and E-W extension, shortly after the emplacement of eclogites in this part of the Eastern Segment. Further, they suggested that the regional E-W folding expressed in the aeromagnetic map pattern is Sveconorwegian and took place during amphibolitization and initial exhumation of the southern part of the Eastern Segment. However, in Paper IV it is argued that the NW-SE to E-W mega-scale folding in the northeastern part of the southern Eastern Segment, as well as the NW-SE to E-W penetrative foliation and lineation in the investigated part of TIB were produced during the c. 1.43 Ga Hallandian-Danopolonian orogeny. Hence, it seems possible that the Eastern Segment consists of different domains, with different structural and metamorphic characteristics, as seen in Figure 7. However, the linkage between these domains is not obvious, although the magnetic anomaly patterns suggest the occurrences of several different blocks in the Eastern Segment.

The Sveconorwegian orogeny was caused by collision between Fennoscandia and another major plate, resulting in reworking of large parts of the Sveconorwegian Province (cf. Bingen et al. 2008a, 2008b). However, it is suggested that the high-grade effects of the Sveconorwegian orogeny did not reach the present-day western border of the Protogine Zone in the investigated area (Paper IV). Nevertheless, Sveconorwegian movements along the shear zones of the Protogine Zone must have occurred (cf. Andréasson & Dallmeyer 1995; Söderlund et al. 2004a). Block movements and erosion were probably greatest in the final stage of the Sveconorwegian orogeny, although various movements possibly also did occur in the time-interval 1.6-0.9 Ga. Both small- and large-scale crustal block movements within and between the segments supposedly occurred (cf. Andersson 2001). These mechanisms caused large scale

exhumation of the high-grade metamorphosed southern Eastern Segment as well as exhumation of the low-grade metamorphosed westernmost TIB-2 and the northern Eastern Segment (Fig. 8). Block movements within the TIB have also been identified e.g. along the boundary between the Småland-Värmland Belt and the Dala Province. This boundary is probably of tectonic nature, since the Småland-Värmland Belt in that area appears to have moved up relative to the dominantly volcanic Dala Province in the east (cf. Magnor et al. 1996).

Different tectonic processes have been proposed for the uplift of the Eastern Segment relative to the TIB and different authors have described the Protogine Zone e.g. as a thrust front (e.g. Berthelsen 1980; Larson et al. 1990; Wahlgren et al. 1994), the shear zones along which the Eastern Segment was uplifted in an extensional regime (e.g. Andréasson & Rodhe 1990; Söderlund 1999), or the thrust front developed as the subducted Eastern Segment was exhumed from mantle depths by eastward movement over the TIB (Austin Hegardt 2000).

The theory that the Eastern Segment represents a metamorphic core complex, as suggested by Söderlund (1999), is favoured here, with exhumation caused by a regional E-W extension, along the Protogine Zone. This is consistent with the steep shear zones occurring along the Protogine Zone south of lake Vättern. If the Protogine Zone would represent a thrust front, the relatively undisturbed and only weakly metamorphosed 1.0 Ga Almesåkra Group (Rodhe 1987), which is located c. 10 km east of the Protogine Zone (Fig. 3), probably would have been (at least somewhat) tectonically disturbed. Alternatively, the thrust front must have been active before the deposition of these supracrustal rocks, i.e. before c. 1.0 Ga.
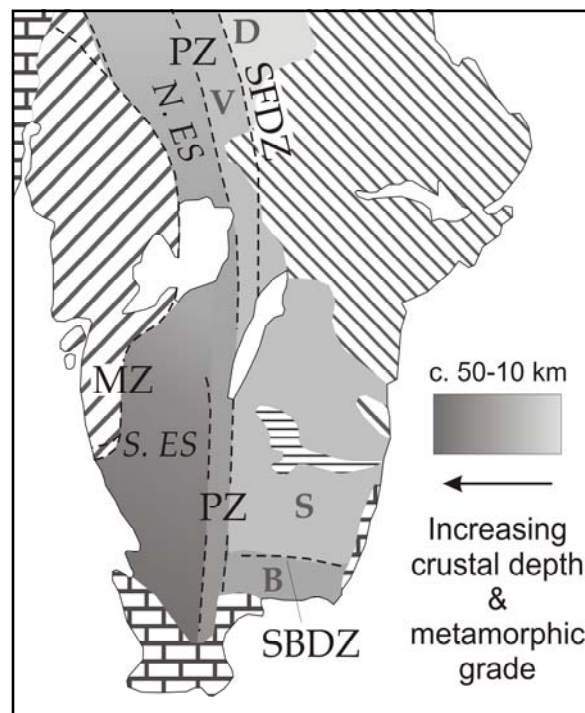

Fig. 8. Schematic map of S. Fennoscandia, based on a sketch by Åke Johansson, illustrating the concept of different crustal exposure levels within the Blekinge Province (B), the Småland (S) – Värmland (V) Belt and the Dala Province (D) of the TIB, as well as the Eastern Segment (ES) of the Southwest Scandinavian Domain. The different shades of grey represent the crustal depth and metamorphic grade, which in general increases toward the SW. The objective of the figure is to show the nature of the Protogine Zone and the metamorphic grade is due to the combined effects of the Sveconorwegian (1.10-0.92 Ga) and Hallandian-Danopolonian (1.45-1.42 Ga) orogenies. The figure is based on references given in Table 1. MZ: Mylonite Zone, PZ: Protogine Zone, SBDZ: Småland Blekinge Deformation Zone, SFDZ: Sveconorwegian Frontal Deformation Zone.

The preservation of eclogites in the Eastern Segment (e.g. Möller 1998; Austin Hegardt et al. 2005) does require rapid cooling, which could be explained by a buoyancy-driven uplift related to the exhumation of a subducted continental crust slab (Austin Hegardt 2000). Subduction-related calc-alkaline magmatism is, however, lacking to the west of the Mylonite Zone.

Instead extension and/or orogenic collapse may explain the exhumation of these high-pressure rocks (cf. Platt 1993). Evidence for repeated regional E-W extension originates from e.g. dolerite dykes and other N-S trending intrusions occurring parallel to the Protogine Zone and the Sveconorwegian Frontal Deformation Zone. Söderlund et al. (2005) and Söderlund & Ask (2006) dated a number of these rocks at c. 1.56, 1.22, 1.20 and 0.98-0.95 Ga. Dolerite intrusions within and east of the Protogine Zone in southcentral Fennoscandia were interpreted to reflect distal magmatic activity in an extensional back-arc setting. Söderlund et al. (2005) also suggested that there is a clear temporal overlap between exhumation (970–930 Ma) of high-grade metamorphic rocks west of the Protogine Zone and dolerite intrusion to the east (Söderlund et al. 2004a).

During exhumation of the Eastern Segment, the uplift was probably greater in the southern than in the northern part, causing tilting of the entire Eastern Segment, and exposure of different crustal levels (Fig. 8). After erosion of the rocks above the present-day Eastern Segment, the effects of both the Hallandian-Danopolonian and the Sveconorwegian orogenies were revealed. Erosion of rocks above the eastern part of the Eastern Segment and the western part of the TIB, revealed only the effects of the Hallandian–Danopolonian orogeny. In the easternmost part of the Protogine Zone pristine TIB-2 rocks were revealed, whereas east of that area, supracrustal and subvolcanic TIB-1 rocks are exposed (e.g. Paper I & II). This area was apparently unaffected by the c. 1.43 Ga Hallandian-Danopolonian orogeny, apart from the intrusion of subordinate felsic bodies and mafic dykes (references in Table 1).

Conclusions

This thesis has resulted in the determination of geochemical and Sm-Nd isotope signatures and U-Pb ion microprobe zircon dating of extrusive and intrusive rocks in the southern part of the TIB and intrusive rocks in the southeastern part of the Eastern Segment of the Southwest Scandinavian Domain.

Two volcanic sequences with overlapping ages were mapped and investigated in more detail. The Habo Volcanic Suite and the Malmbäck Formation were dated at 1795±13 Ma and 1796±7 Ma, respectively, showing that they are coeval with and are part of the TIB-1 magmatic suite. The Malmbäck Formation comprises fairly well preserved volcanic rocks although mineral parageneses suggest metamorphism at up to epidote-amphibolite facies conditions, whereas metamorphism and deformation in the amphibolite facies has obscured primary textures of the Habo Volcanic Suite. Both suites comprise mafic to felsic components and the Malmbäck Formation includes one of the largest deposits of mafic volcanic rocks within the TIB-1. The mafic volcanic rocks were derived from a juvenile, mildly depleted mantle source, whereas mixing or crustal assimilation between basalt magma and an upper-crustal component probably formed the intermediate to felsic parts.

Twenty-four granitoids across the border zone between the TIB and the Eastern Segment were investigated. Geochemical and isotopic signatures of the investigated granitoids proved to be similar, supporting the theory that the TIB and the Eastern Segment originated from the same type of source and experienced the same type of emplacement mechanisms.

Eighteen of the granitoids have distinct TIB-2 ages ranging between 1710 and 1660 Ma, as determined by U-Pb zircon ion microprobe analyses. Sm-Nd isotopes

suggest that the granitoids, from both the western TIB and the Eastern Segment were derived from a relatively juvenile pre-existing crust with minor contribution of older crust, in an essentially east- to northeast-directed subduction environment.

The U-Pb zircon ion microprobe analyses also dated zircon rims formed between 1460 and 1400 Ma, both in the eastern part of the southern Eastern Segment and in the southwestern part of TIB. It is concluded that leucosome formation and NW-SE to E-W folding in the investigated part of the Eastern Segment as well as NW-SE to E-W penetrative foliation and lineation in the investigated western part of the TIB were produced during the Hallandian-Danopolonian orogeny.

High-K calc-alkaline to shoshonitic trends, REE, spider and discriminant diagrams of the volcanic rocks as well as the granitoids support the idea that the TIB was emplaced in an active continental margin setting, similar to what is seen in the Andes today.

No Sveconorwegian ages were recorded in any of the samples investigated in this project. Nevertheless, it is suggested that late-Sveconorwegian (in addition to earlier) block movements caused uplift of the Eastern Segment relative to the TIB, revealing (1) the highly exhumed metamorphosed Eastern Segment in the west, where the effects of both the Hallandian-Danopolonian and the Sveconorwegian orogenies can be seen, (2) the partly exhumed western TIB-2 rocks showing the effects of the Hallandian-Danopolonian orogeny only, and (3) the easternmost TIB-2 and the supracrustal and subvolcanic TIB-1 rocks in the east, where traces of the Hallandian-Danopolonian orogeny can only be seen as intrusions of subordinate granitic bodies and mafic dykes. Uplift and erosion probably increased toward the southwestern margin of the Fennoscandian Shield, causing tilting of the entire Eastern Segment and exposure of different crustal levels.

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